Plant Physiol. (1972) 50, 191–193

Short Communication

In Situ Measurement of Root-Water Potential[1]

Received for publication August 19, 1971

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This paper describes a psychrometric technique for measuring the water potential of attached growing roots and reports some results obtained with it. This technique was developed as an aid in the analysis of water transport processes in the soil-plant system. Most treatments of water transport in transpiring plants are based on the development of a water deficit in the aerial plant parts. This deficit shows up as a lowered leaf water potential which when transmitted along the plant through various resistances forms a potential gradient from the soil to the leaves. Soil water, if available, moves along this gradient to the various plant parts. In recent years a number of attempts have been made to deal with the soil-plant potential gradient and the associated resistances (1–3, 5, 6, 9). There are, however, very few measurements of the single most important part of this gradient, the soil-root interface, and none come from intact root systems. A measure of the root-water potential as well as of the potential in the adjacent soil should reflect the ability of the plants to extract water from soils of varying potentials and provide useful information regarding the limits of this ability. Also, it should be useful in determining the magnitude of the root resistance to water flow.

MATERIALS AND METHODS

Soil-water potential was measured with commercial ceramic cup psychrometers similar to those described by Wiebe *et al.* (9). These psychrometers were individually calibrated in standard sodium chloride solutions over the expected ranges of temperature and potential. The operating protocol suggested by Rawlins and Dalton was followed (8). A cooling current of 5 ma for 15 sec was used for all measurements.

Root-water potentials were measured with Peltier-effect thermocouple psychrometers designed by the author. The psychrometers (Fig. 1) consisted of small Teflon sleeves with removable top and bottom caps. Slits were cut in opposite sides of the sleeves and in the bottom caps in such a manner that when the two pieces were fitted together a circular hole remained in each side of the psychrometer allowing a root to extend through the psychrometer chamber. The psychrometer was constructed in three pieces so that a number of sleeves and bottom caps with various size holes could be used with the same thermocouple to accommodate roots of various diameters. The length of the caps was such that when they were inserted and rotated 90°, both slits were sealed off, and the psychrometer was thus made airtight for calibration. Calibration was effected by placing standard NaCl solutions in the calibration well (E in Fig. 1), assembling the psychrometer and placing it in a controlled temperature bath for measurement. The operating protocol and calibration procedures were the same as for the soil psychrometers.

The root psychrometers were attached either to the primary root at the time the seedlings were transferred to the soil or to secondary roots after the plants had become well established. In the latter case, the soil was carefully removed from around the root to permit attachment. The root was washed with nutrient solution to remove any adhering soil particles, then blotted dry before the psychrometer was attached. A watertight seal was made with stopcock grease, and the soil was then replaced carefully so as not to disturb the seal. Care must be taken that grease does not cover the root inside the chamber since this will result in erroneous readings. The size of the root psychrometers affects linearity of response but this may be determined during calibration. Furthermore, the chamber should be small enough in diameter so that the root tissue within the psychrometer chamber will be in equilibrium with that outside. This points out the basic asumption we have made in this work which is that the root segment inside the psychrometer chamber reflects conditions in the contiguous regions of the root which are in contact with the soil (*i.e.*, the psychrometer does not change the potential of the root segment). In any case, the main conducting pathways will remain unimpeded, so the transmission of the driving force from the shoot should not be affected.

Soil psychrometers were installed in close proximity to each root psychrometer so that the soil-water potential could be measured and the potential gradient from the bulk soil to the root surface estimated.

All measurements were taken and recorded with a low speed sequential scanning system constructed in this laboratory.

In the experiment reported corn seeds, *Zea mays* L. (Funk's 508W), were soaked overnight in distilled water and germinated for 3 days in the dark on wet paper towels. The seedlings were then transferred to 40-liter sand-filled containers and watered with half-strength Hoagland's No. 1 nutrient solution (4). A relatively large volume of sand was used to minimize rapid temperature fluctuations which make water potential measurements difficult to interpret. The sand was kept near field capacity until the beginning of a drying cycle.

Plants were grown in a growth chamber with a 14 hr photoperiod and day and night temperatures of 29 and 20 C, respectively. Lighting was fluorescent with supplemental incandescent lamps. The light intensity, measured with a YSI Model 65 radiometer using a 6551 probe, at plant midheight was approximately 1×10^5 ergs cm^{-2} sec^{-1}. Water potential measurements were made daily at 1400 EST ± 30 min and watering, if necessary, was done immediately afterward.

Stomatal diffusion resistance was measured at the same time with a diffusion porometer similar to that described by Kanemasu *et al.* (7). All resistance measurements were made

[1] This work was supported by National Science Foundation Grant GB-8157.

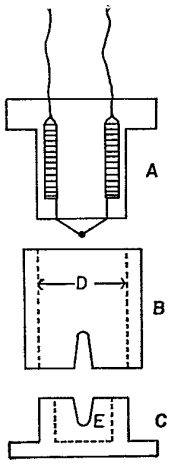

FIG. 1. Schematic diagram of the root psychrometers. **A:** Top cap with the thermocouple and copper heat sinks; **B:** main chamber; **C:** bottom cap with calibration well (**E**). Dimension **D** in this case was 0.95 cm, and the total volume was approximately 0.54 cm^3.

on the lower surface of the second leaf from the apex of the plant.

RESULTS AND DISCUSSION

The data for a single plant are shown in Figure 2. In this case, the root psychrometer was attached to the primary root 17 cm below the seed. Both the root psychrometer and its associated soil psychrometer were at a depth of 20 cm below the surface of the sand. Soil-water potential was also monitored at the 3-cm and 50-cm depths. These data are not shown but will be mentioned as needed.

The soil-water potential at the 20-cm depth remained unchanged for approximately 3 weeks after the cessation of watering so that by day zero in Figure 2 the plant was 40 days old. By this time, however, the surface soil had already dried to less than −50 bars which was the limit of our calibration. Soil-water potential at the 50-cm depth never fell below −1 bar.

Stomatal resistance rose to moderate levels (5–10 sec cm^{-1}) early in the experiment in response to drying in the upper sand layers. Further increases did not occur until day 8 when the resistance rose sharply to nearly 34 sec cm^{-1}. By this time the lower sand levels had dried significantly, and it was apparent that the root- and sand-water potentials were converging rapidly. In addition all the leaf tips were rolled at this time and the two youngest leaves showed pronounced folding along their entire length. By day 9 the sand at the 20 cm depth had dried to −15.1 bars and the stress had become severe. All the leaves were tightly rolled and the older leaves were drying out from the tips. At this time the root-water potential had dropped to only −10.3 bars so the potential gradient between this particular root segment and its environs was reversed. The plant was watered immediately after measurement on day 9 and by the next day most of the outward signs of stress had disappeared. The leaves were all unrolled and the only signs of permanent damage were dry areas on the terminal third of the four oldest leaves and scattered spotting on all but the two youngest leaves.

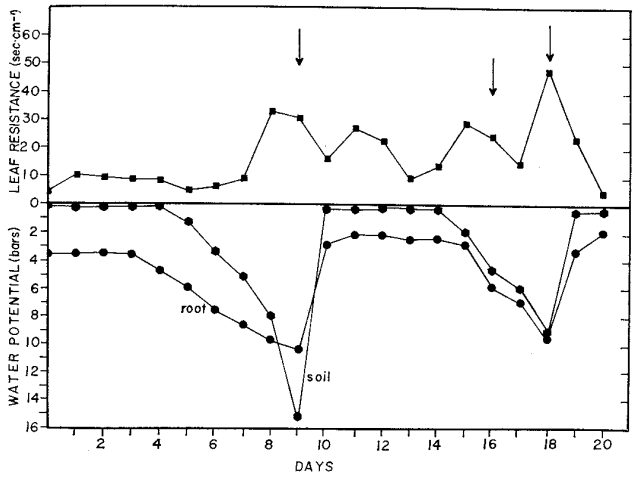

FIG. 2. Root- and soil-water potentials at the 20-cm depth during two drying cycles. Watering times are indicated by (↓).

Stomatal resistance decreased rapidly after watering but then resumed a high value and declined more slowly thereafter. The soil-water potential rose to its former field capacity value but the root-water potential reached values higher than it had previously.

Once during the second drying cycle a small quantity of water was added to the surface soil. The container was covered with plastic film at this time so that vapor phase movement within the soil would be facilitated. In this manner it was possible to slow down the rapid drying of the deeper soil layers. This treatment was responsible for the irregular appearance of the curves and appeared to influence stomatal resistance more than root-water potential.

Stomatal resistance on day 17 was only 14.5 sec cm^{-1} because of the light watering on the previous day. However, the leaves were flaccid and wilted with only the tips slightly rolled. Signs of severe stress did not appear until the next day when all the leaves were tightly rolled and the stomatal resistance reached its maximum. Root- and soil-water potential values seemed to be converging again at day 18. The plant was heavily watered at this time. The leaves and roots recovered nicely, and the stomatal resistance fell more rapidly than before.

The soil-water potential at the 3 cm depth was less than −50 bars throughout the first drying cycle. After watering, it rose to greater than −1 bar but fell again rapidly. It did not rise again until after the light watering on day 16.

Although no measurements of leaf-water potential were made in this experiment, stomatal resistance measurements and the rolling of leaves indicated that the plant had become severely stressed during the two drying cycles. Despite this, the root appeared able to decrease in potential to only −10.3 bars during the first drying cycle, thus reversing the potential gradient between the soil and the root surface. During the second cycle the root again appeared to be approaching an equipotential point of roughly the same order of magnitude.

Although the root-water potential was well correlated with soil and other plant phenomena in this case, care must be exercised in generalizing from such limited data. In this instance the root system was limited in extent and the root and soil psychrometers were in the area of highest root density, and this accounts for the very good correlation between root and soil-water potentials at the 20-cm depth and stomatal resistance. The potentials developed in other parts of the root system are unknown at this time, as is the variability from root to root and with changes in root chamber geometry.

The availability of root psychrometers should encourage further study of the water potentials of roots and soil.

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